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Citation for published version:

Bisby, LA, Chen, J-F, Li, SQ, Stratford, TJ, Cueva, N & Crossling, K 2011, Strengthening Fire Damaged Circular Concrete Columns with FRP. in *Advanced Composites in Construction 2011*. NetComposites Ltd., Warwick, pp. 130.

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Early version, also known as pre-print

Published In:

Advanced Composites in Construction 2011

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Strengthening Fire Damaged Circular Concrete Columns with FRP

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ABSTRACT

Extensive research has shown that fibre reinforced polymer (FRP) wraps are very effective for strengthening concrete columns for increased axial and flexural load and deformability, and this technique is now widely used around the world. The study reported in this paper extends the FRP confinement technique to strengthening fire damaged concrete columns. An experimental program was undertaken to study the compressive strength and stress-strain behaviour of both unconfined and FRP confined concrete cylinders after being heated to elevated temperatures for up to four hours and cooled to room temperature. The results show that FRP confinement is highly effective for enhancing the load carrying capacity of even severely fire damaged concrete columns.

INTRODUCTION

Externally bonded fibre reinforced polymer (FRP) circumferential wraps are a method of choice for reinstating or enhancing the strength and deformation capacity of concrete columns. A wealth of experimental evidence exists to support such applications of FRPs, and many analytical models are available for use in designing FRP strengthening schemes for both circular and rectangular concrete columns at ambient temperatures [1, 2]. An increasing body of work [3, 4] has also examined the performance during fire of reinforced concrete columns which have been strengthened with FRP wraps. However, a potentially useful application of FRP confinement of concrete which has received only limited attention to date is for strengthening fire-damaged concrete columns; i.e. columns which have been exposed to elevated temperatures or which have experienced heat-induced reduction in the mechanical properties of their constituents [5]. This paper presents the results of an experimental program conducted to study the effectiveness of FRP confinement for enhancing the strength and axial/lateral stress-strain response of fire damaged circular concrete columns. Various levels of heat-induced damage to the concrete are examined, covering the full range of relevant fire exposure temperatures.

It should be noted that the focus of this study is on FRP strengthening of fire damaged concrete, rather than on understanding damage to the concrete itself on which a large body of knowledge is available (e.g. [7-11]). The use of FRP wraps for strengthening concrete columns is widely accepted within the structural engineering community, and codified design procedures are available for the design of FRP strengthening schemes to increase the axial load carrying capacity of columns under ambient temperatures (e.g. [12]). The primary objectives of the research presented in this paper were:

- to observe the impact of unstressed heating on the residual strength and axial/lateral stress-strain response of short concrete cylinders loaded in uniaxial compression;
- to demonstrate and quantify the effectiveness of externally bonded FRP hoop wraps (i.e. FRP confinement) for reinstating or increasing the strength of fire-damaged circular concrete compressive elements; and
- to investigate the impacts of varying the unconfined concrete compressive strength on the performance of FRP confinement of concrete (i.e. fire-damaged concrete will have virtually identical grain structure to the undamaged concrete but will have reduced strength and considerable pre-existing micro-cracks in the cement paste, etc.

EXPERIMENTAL PROGRAM

Experimental Design

The experimental program consisted of uniaxial compressive tests on 33 plain or FRP wrapped concrete cylinders, as outlined in Table 1. Test parameters included: (1) the presence of FRP confinement, (2) the target exposure temperature, and (3) the total heating duration. All tests were performed in triplicate to verify the repeatability of the results, and all other factors which are known to influence the residual properties of concrete were carefully controlled to avoid experimental uncertainties, as described below.

Table 1 shows that the columns were either unwrapped or wrapped in the hoop direction with a single layer of the SikaWrap Hex 230C unidirectional carbon fibre/epoxy FRP system [13]. This is typical of the various systems marketed globally for strengthening concrete structures. The manufacturer-specified properties for this FRP system state an ultimate tensile strength of 4100 MPa at a tensile strain of 1.7% with a nominal thickness of 0.12mm. The FRP was applied using a hand lay-up procedure.

The cylinder exposure temperatures were selected so as to cover a reasonable range of temperatures sufficiently high to cause noticeable deterioration in the residual mechanical properties of the concrete (i.e. above about 300°C [7]), while not being so high as to make repair of the concrete indefensible in practice (i.e. remaining below about 600-700°C [9]). The default total duration of heating was taken as 120 minutes, which represents a typical structural fire resistance rating for a 30+ metre tall multi-storey building in the UK [14]. A single group of specimens with a hold temperature of 686°C was heated for an extended total duration of 240 minutes to determine if the duration of heating had a noticeable impact on the results under the most severe heating condition.

Fig. 1 provides details of the test specimens, including dimensions and the FRP wrap configuration. All specimens were unreinforced concrete cylinders, 100mm in diameter and 200mm in height. All were cast from C25/30 ready-mix concrete with a maximum aggregate size of 10mm. The columns were cured under ambient conditions for 60 days before being heated or wrapped with FRP. Two thermocouples, one at mid-height and one at quarter-height, were placed on the central axis inside one specimen in each group to monitor internal temperatures during heating. All columns were pressure washed to remove

scaling and residue prior to being subjected to thermal exposures (where applicable). After the heating exposure, a single layer of carbon FRP was applied in the hoop direction, with a hoop overlap of 100mm. The FRP wrapped specimens were allowed to cure at room temperature for a minimum of three weeks before testing. Immediately prior to testing each column was capped with rapid-set mortar. Finally, both unwrapped and FRP wrapped columns were painted with a high contrast texturing effect; this was done to enable the use of digital image correlation for strain measurement during testing (discussed below).

Table 1. Details of the experimental program and selected test results

Group ^a	FRP (Y/N)	Target exp. temp. (°C)	Heat time (mins)	Failure mode ^c	Failure stress (MPa)		Axial strain at peak stress (%)		Hoop strain at peak stress (%)	
					Test	M ± σ	Test	M ± σ	Test	M ± σ
U-20-00	N	20	--	Shear	30	28.0 ± 5.3	0.20	0.25 ± 0.07	0.13	0.21 ± 0.11
				Cone	22		--		--	
				Cone	32		0.30		0.29	
W-20-00	Y	20	--	FRP rupture	63	59.0 ± 5.3	--	1.19 ± 0.19	--	1.01 ± 0.01
				Mixed	61		1.32		1.02	
				FRP rupture	53		1.06		1.00	
W-20-00* ^b	Y	20	--	FRP rupture	55	57.0 ± 2.0	0.97	1.00 ± 0.06	1.03	1.00 ± 0.02
				FRP rupture	59		1.08		0.10	
				FRP rupture	57		0.97		0.99	
U-300-120	N	300	120	Cone	30	27.0 ± 2.6	0.28	0.44 ± 0.19	0.35	0.83 ± 0.60
				Cone	26		0.40		0.64	
				Cone	25		0.65		1.51	
W-300-120	Y	300	120	Mixed	63	61.0 ± 2.0	1.31	1.32 ± 0.01	1.09	1.02 ± 0.07
				FRP rupture	61		1.32		1.01	
				Mixed	59		1.33		0.96	
U-500-120	N	500	120	Cone	21	20.0 ± 1.0	0.50	0.49 ± 0.28	1.38	1.04 ± 0.68
				Shear	20		0.21		0.26	
				Shear	19		0.76		1.48	
W-500-120	Y	500	120	Mixed	58	54.0 ± 6.1	1.53	1.53 ± 0.18	1.08	1.04 ± 0.04
				FRP rupture	47		1.71		1.00	
				Debonding	57		1.35		1.04	
U-686-120	N	686	120	Cone	14	14.7 ± 0.6	0.39	0.37 ± 0.11	0.60	0.81 ± 0.18
				Shear	15		0.48		0.92	
				Shear	15		0.25		0.91	
W-686-120	Y	686	120	Debonding	50	51.3 ± 3.2	1.84	1.66 ± 0.26	1.28	1.05 ± 0.20
				Mixed	55		1.36		0.96	
				FRP rupture	49		1.78		0.91	
U-686-240	N	686	240	Cone	15	11.7 ± 3.1	0.82	0.48 ± 0.30	2.76	1.65 ± 1.03
				Shear	9		0.24		0.74	
				Cone	11		0.37		1.44	
W-686-240	Y	686 ^c	240	Debonding	48	51.0 ± 3.6	1.92	1.75 ± 0.17	0.91	1.00 ± 0.08
				Mixed	55		1.75		1.01	
				Mixed	50		1.59		1.08	

NOTES:

^a All tests were performed in triplicate.

^b These specimens were not pre-dried prior to testing.

^c FRP wrapped failure modes: FRP rupture = tensile rupture of the FRP wrap in the hoop direction outside the overlapping region; Debonding = debonding of the FRP wrap in the hoop direction within the overlapping region; and Mixed = a combination of FRP rupture and debonding failure modes.

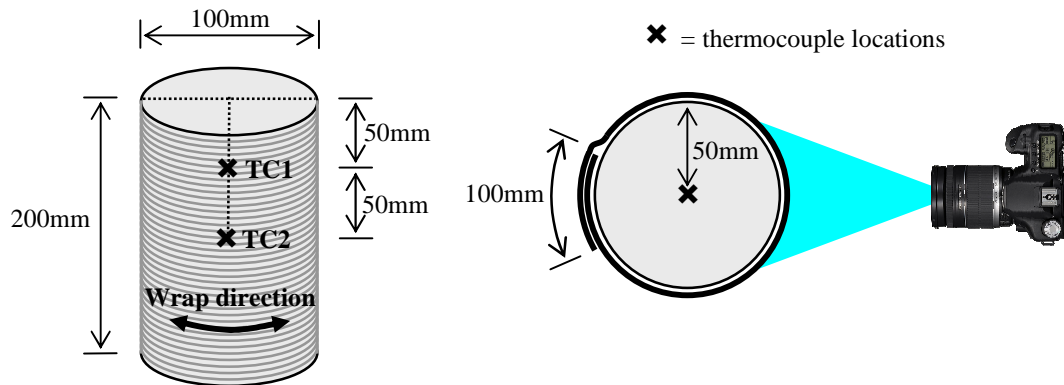


Figure 1. Details of test specimens, FRP wrap configuration, thermocouple locations, and camera positioning with respect to the FRP overlap

To prevent explosive cover spalling during heating all specimens were conditioned in a drying oven for seven days at 90°C before being placed in the furnace. While this is not representative of a real fire scenario, when explosive spalling occurs during fire it is generally limited to the cover concrete. No spalling whatsoever was observed during heating for the tests presented herein. In addition, because it is well known that the recovery time between thermal exposure and mechanical testing is an important factor influencing the residual properties of heated concrete [9], care was taken to ensure that specimens were treated consistently. All specimens were wrapped between two and six days after being heated, were capped two or three days before testing, and were tested between 16 and 18 days after heating at an age since casting between 69 and 101 days.

Heating Regimes

The specimens were heated in groups of three specimens per exposure inside an electric furnace with internal dimensions of 230mm × 230mm × 510 mm. For a given exposure temperature (i.e. 300°C, 500°C, or 686°C) the furnace was programmed to heat as quickly as possible up to the desired temperature and then to hold that temperature for 120 or 240 minutes. The furnace was then turned off and allowed to cool slowly to ambient. Typical heating profiles for the thermal exposures are given in Fig. 2. These profiles include the intended furnace temperatures as well as temperatures recorded at TC1 in the specimens (refer to Fig. 1). It should be noted that 120 minutes was insufficient to reach a target temperature of 700°C, and the actual furnace temperature achieved for the 700°C soak temperature was 686°C. The approximate heating rate was in the range of 5-15°C/minute.

Also shown in Fig. 2 is the standard temperature-time curve (ISO 834) used for structural fire resistance testing in Europe [15]. Clearly, the furnace used in the current study was unable to achieve heating rates that are representative of the standard fire. However this is not critical because the current study is concerned primarily with confinement of concrete within a column's core. Within the core concrete the heating rates and peak temperatures

experienced would be moderated by the thermal protection of the cover concrete, and would likely be similar to the exposures reproduced by the heating profiles imposed herein.

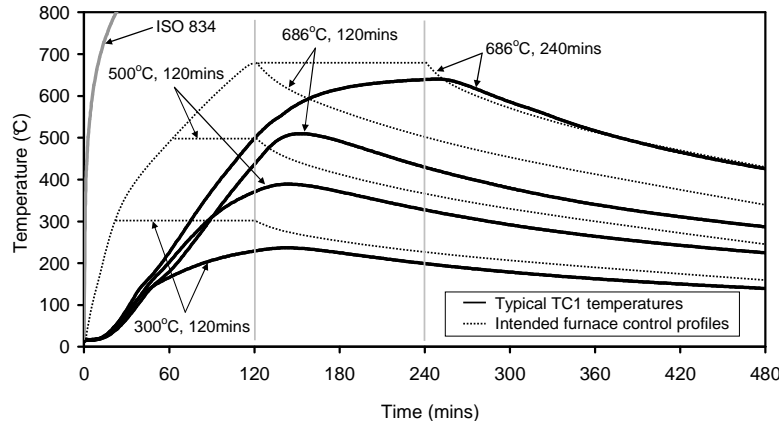


Figure 2. Typical heating profiles recorded for samples under various thermal exposure temperatures and durations in the current study

Structural Testing & Optical Strain Measurement

All specimens were tested under concentric, monotonic, uniaxial compression using a 1000kN structural loading frame. Testing was performed under load control at a rate of approximately 100kN/min. The column bases were rotationally restrained during testing while the tops were effectively pinned (by bearing against a load cell with a spherical seat).

The total applied load was monitored during testing using a load cell, while axial and hoop strains were monitored using a digital image correlation technique; this has been described and validated previously by Bisby and Take [16]. A Canon EOS 5D Mark II camera was used to capture images of the columns every five seconds using a remote trigger during testing. The load corresponding to each image was known from the load versus time curve. This means that strain readings were taken approximately every 5kN. The camera was located opposite to the FRP hoop overlap, as shown in Figs 1 and 3. After testing, the recorded images were correlated to known applied loads and processed using bespoke pixel tracking software, GeoPIV, coded by White et al. [17]. Briefly, the software is used to define a patch of pixels in the initial image and this patch is tracked in subsequent images. The location and size of the patch can be chosen anywhere within the field of view of the camera, and it can be tracked in any direction. By defining pairs of patches, in-plane strains can be computed over any chosen gauge length and in any direction. Bisby and Take [16] have validated this technique by comparison with bonded foil strain gauges for measuring hoop and axial strains on circular FRP confined concrete cylinders. The image correlation analysis as implemented herein is accurate to better than one tenth of one pixel [17]. With virtual strain gauge lengths of 50mm (hoop) and 100mm (axial), as applied in the current analysis, strain measurement resolutions better than 0.01% (hoop) and 0.005% (axial) were achieved. Take and Kemp [18] have validated this approach for measuring hoop strains in cylindrical specimens, even though the hoop displacements are slightly out of plane. The

authors have previously used the optical technique to quantify the variation of hoop and axial strains in FRP wrapped concrete columns and have found that considerable variability and volatility exist in both directions [19], and average strains must therefore be calculated. The optical technique allows many individual virtual strain gauges to be examined; this is not possible using foil strain gauges.

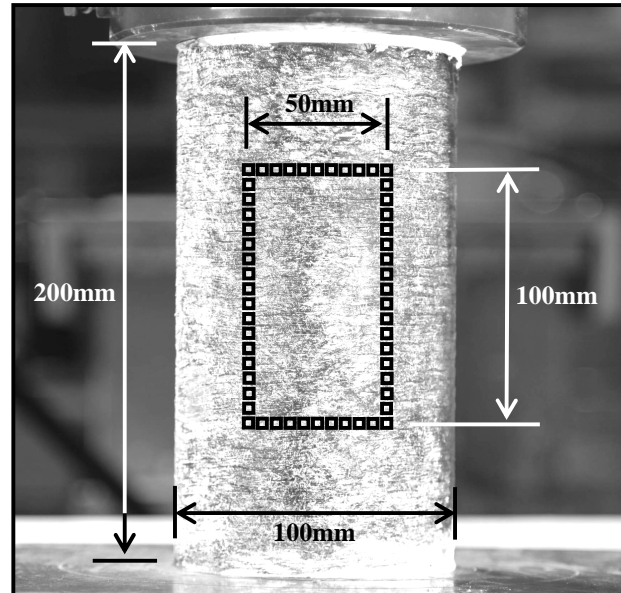


Figure 3. Typical image captured during testing of an FRP wrapped concrete cylinder (strain rectangle used to calculate hoop and axial strains also shown schematically)

For the analysis presented in this paper, strains were measured using a ‘strain rectangle’; shown schematically in Fig. 3. Hoop strains were measured as the average of 50 virtual strain gauges distributed over the height of the middle 100mm of the specimens, each with a gauge length of 50mm. Axial strains were measured as the average of 20 strain readings distributed over the width of the middle 50mm of the specimens’ diameter, each with a gauge length of 100mm. All strains were measured opposite the FRP overlapping region.

EXPERIMENTAL RESULTS & DISCUSSION

Table 1 provides a summary of test data, including peak stress, hoop strain at failure, and axial strain at failure for each group of three specimens. The individual specimens are distinguished using letters A, B, and C. Strain data were lost for U-20-00-B & W-20-00-A.

Residual Properties of Unconfined Concrete

Fig. 4a provides a graphical summary of compressive strength results for all of the test specimens, and Fig. 4b shows only the unconfined test results compared against Freskakis

et al.'s [11] upper and lower bounds for residual strength. The data markers in these figures distinguish between samples that were pre-dried at 20°C (W-20-00*) from all the rest which were pre-conditioned at 90°C, and those that were heated for 240 minutes (U-686-240 and W-686-240) rather than the default 120 minute exposure. The solid lines in Fig. 4a show the average trends for the unwrapped and wrapped specimens, respectively. Only results from preconditioned specimens with heating exposures of 120 minutes were included when calculating the average trends.

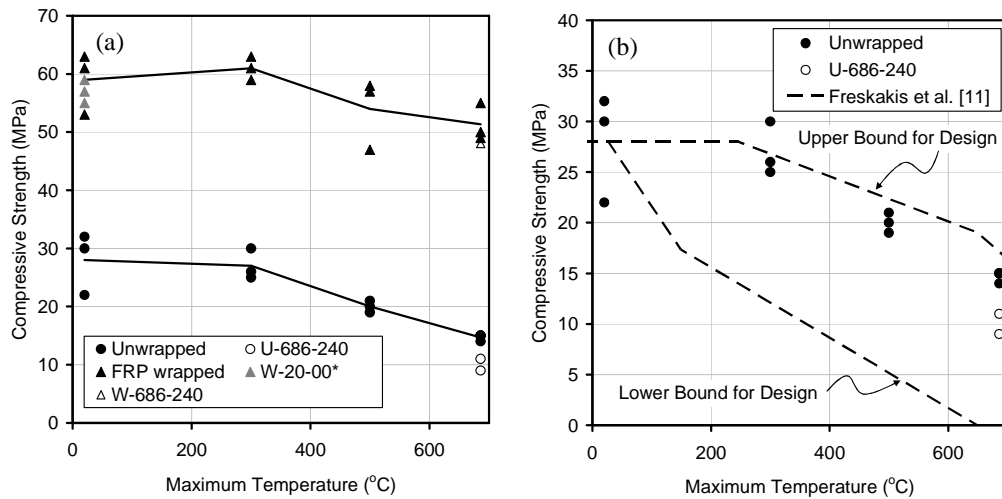


Figure 4. Effects of exposure temperature on (a) specimen ultimate strengths and (b) unconfined plain concrete strength with comparison against literature

It is clear from Fig. 4a that exposure to elevated temperatures caused a reduction in the residual strength of the concrete, and that considerable reductions were experienced when the concrete was heated to temperatures in excess of 300°C. This observation is consistent with previous research on the residual properties of fire-exposed concrete, as shown in Fig. 4b [11], although data from the current study sit close to the expected upper bound curve despite being heated without applied loading. Concrete exposed to 500°C and 686°C for 120 minutes experienced reductions in strength in the order of 29% and 50%, respectively. Concrete exposed to 686°C for 240 minutes experienced a strength reduction in the order of 58%. There was no obvious influence of pre-drying the cylinders, at least as far as the strength of unheated wrapped samples was concerned. The influence of pre-drying on the residual properties of heated concrete warrants further investigation, as it is hard to imagine that the effect of pore water movement and evaporation during heating is unimportant.

Fig. 4 also confirms that very large increases in compressive strength can be achieved for both undamaged and fire damaged concrete by applying FRP hoop wraps. The FRP wraps were able to easily reinstate the original strength of the damaged concrete specimens. It is important to recognise, however, that the residual stress-strain characteristics of the concrete are not fully reinstated by FRP wrapping. To demonstrate this, Fig. 5 provides the observed axial stress-axial strain and axial stress-hoop strain response for all pre-dried

samples exposed for 120 minutes. This figure shows the impacts of heating on the strength, stiffness, and stress-strain response of both unwrapped and FRP wrapped columns. While considerable variability between individual specimens is evident in Fig. 5, the overall impacts of heating and FRP wrapping are reasonably clear. For the unconfined concrete specimens, exposure to elevated temperatures causes a reduction in compressive strength (as noted above), but also a reduction in the modulus of elasticity (which appears to be considerable even at an exposure temperature of 300°C) and an increase in the strain at peak stress. Since the tests were performed under load control, no post-peak softening response was observed. The dilatency of the concrete increases drastically due to heating, as does the variability of both axial and hoop strain measurements, possibly indicating that non-homogeneities in the concrete are exacerbated by thermal exposure.

Fig. 5 also shows that the FRP wraps, while highly effective for strengthening the fire-exposed concrete, do little or nothing to increase the axial stiffness at loads less than the residual peak unconfined strength, which is similar to the same phenomenon which is well known for FRP confined undamaged concrete. This is an important observation for practical application of FRP wraps in strengthening fire-damaged concrete structures. Care is needed to ensure that the service loads on a fire damaged column remain below about 70-80% of the peak strength of the unconfined fire-damaged concrete so as to avoid creep and excessive damage to the core concrete and possible sudden failure in the event that the FRP wrap should become ineffective (due to fire, vandalism, etc.).

The FRP wrap drastically reduces the dilatency of the fire-damaged concrete at all load levels. While this suggests that the FRP wrap should be more engaged for a fire-damaged column, it must be recognized that the hoop stiffness of the fire damaged concrete is also reduced due to heating, so that the interaction of the FRP with the dilating concrete core appears to be similar for all specimens regardless of the level of thermal damage.

Effectiveness of FRP Confinement for Fire-Damaged Concrete

Fig. 6 highlights the effectiveness of FRP confinement for increasing the strength of fire damaged concrete by plotting the strength increase due to FRP wrapping, both as a percentage of the unconfined concrete strength (Fig. 6a) and as an absolute strength increase (in MPa), over and above the unconfined strength (Fig. 6b), versus exposure temperature. It is evident that FRP confinement results in a proportionally greater improvement in strength for higher levels of damage.

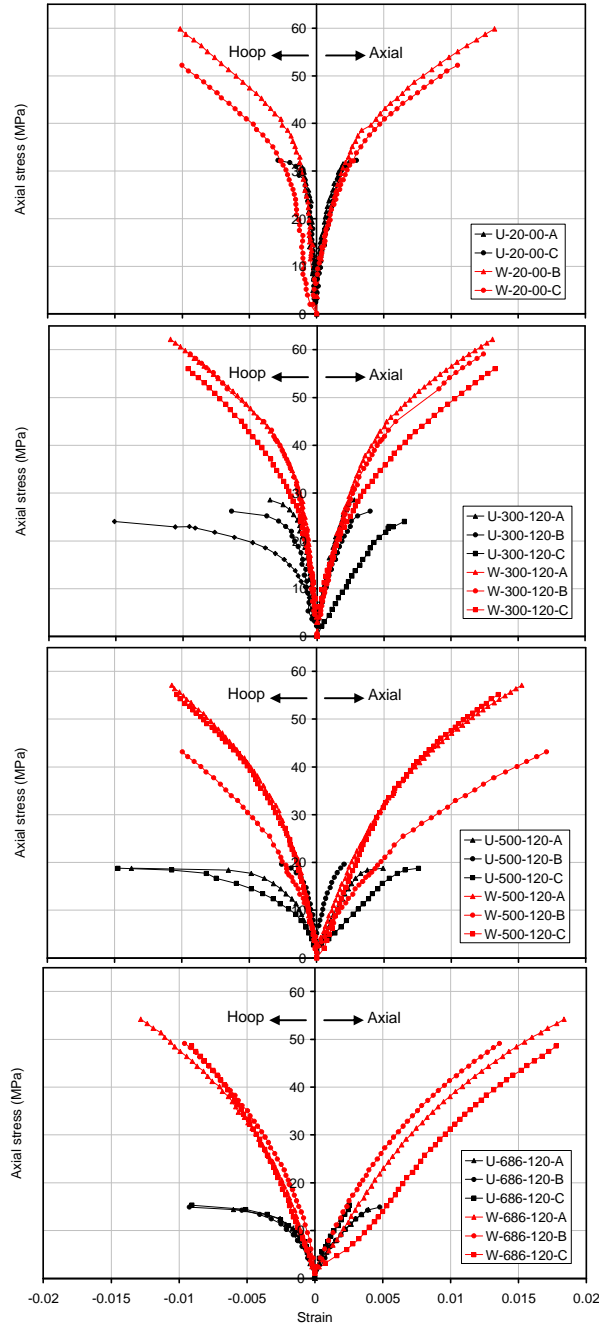


Figure 5. Axial stress versus axial strain and axial stress versus hoop strain

However, the average test data line in Fig. 6b shows that the absolute strength increase due to FRP wrapping is reasonably consistent across all levels of thermal damage (or unconfined strength). This suggests that the enhancement of concrete strength depends not on the unconfined strength, as has been suggested by others [20], but on the fundamental physical characteristics of the concrete mix behaving as a granular material or as a mechanism beyond the peak unconfined strength. This phenomenon may also be explained by the shear failure wedges [21] if the failure plane is not affected by the thermal exposure.

This also suggests that a model to predict the strength enhancement of fire damaged concrete by FRP wraps may assume the same level of strength enhancement as would be predicted for an unheated specimen of the same type.

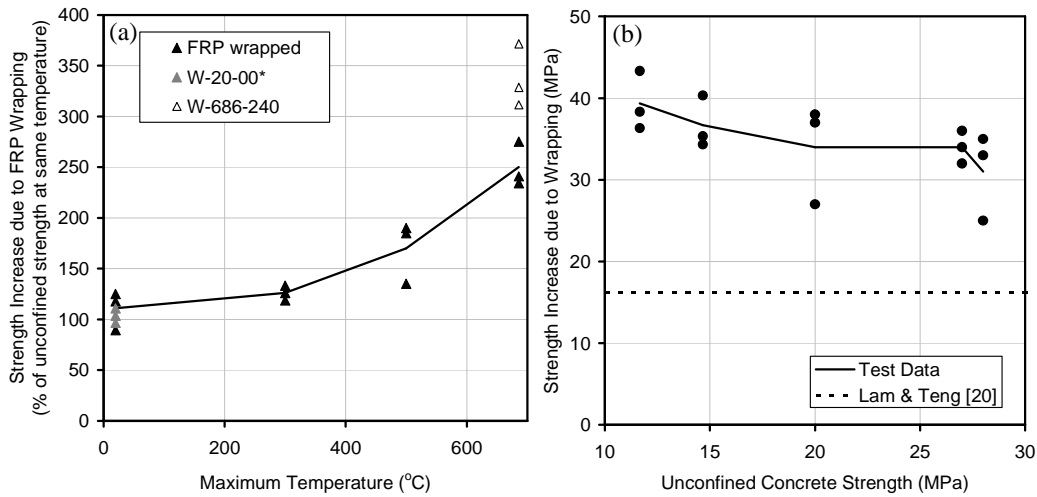


Figure 6. Effect of unconfined concrete strength on variation of absolute strength increase

Axial & Hoop Strains

Fig. 7 shows the impacts of FRP confinement on the axial (Fig. 7a) and hoop (Fig. 7b) strains recorded at failure for both wrapped and unwrapped columns. Hoop strains are shown only for FRP wrapped columns, since the data for the unwrapped columns displayed unacceptable variability. Fig. 7a shows that the axial strains of the FRP confined concrete are drastically increased (by more than 100% in all cases) compared to the unconfined concrete. It also suggests that the level of enhancement of axial strain also remains constant with increasing temperature (as observed for strength enhancement in Fig. 6b).

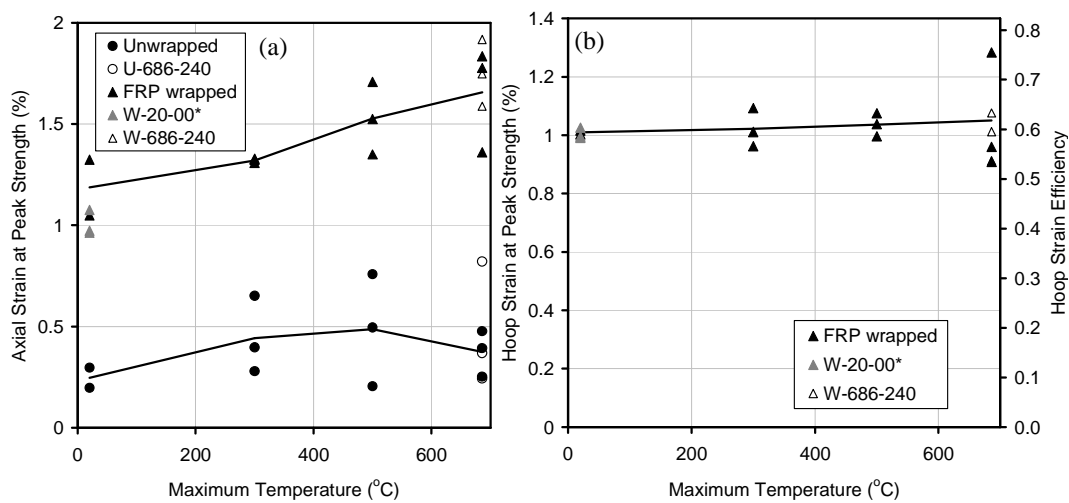


Figure 7. Effect of exposure temperature on measured (a) axial & (b) hoop strains at failure

Fig. 7b shows that the hoop strain at failure (i.e. the tensile rupture strain in the FRP wrap) remains essentially constant with increasing exposure temperature. This suggests that the confinement provided by the FRP at the ultimate state is not affected by thermal damage to the concrete, as expected. Furthermore, the observed hoop strain at failure is in the range between 0.9% and 1.3% for all wrapped specimens, corresponding to between 53% and 76% of the manufacturer specified ultimate strain for the FRP material obtained from coupon tests. This is consistent with previous research on the hoop strain efficiency of FRP wraps for confining circular concrete columns [16, 19, 22, 23].

CONCLUSIONS

The following conclusions can be drawn based on the testing presented in this paper:

- Exposure to elevated temperature adversely impacts the residual strength, stiffness, and axial/lateral stress-strain response of plain concrete cylinders tested under uniaxial compression after cooling to room temperature. The reductions in strength observed in the current study are consistent with data available in the literature.
- The effectiveness of externally bonded FRP hoop wraps for reinstating and enhancing the strength of fire-damaged concrete compressive elements has been demonstrated for exposure temperatures up to a practical upper limit in the range of 700°C. FRP confinement is extremely effective for reinstating the strength of equivalent unheated concrete, although it must be noted that the stiffness of the heat damaged concrete within the typical service stress range is not enhanced by FRP wrapping.
- The enhancement of strength due to FRP confinement appears to be independent of the unconfined concrete strength, but rather depends on the physical characteristics of the concrete (and the influence of these on the resulting failure mechanism); this appears also to be true for the axial strain enhancement due to FRP wrapping.

ACKNOWLEDGEMENTS

We would like to acknowledge the School of Engineering, Univ. of Edinburgh. Bisby acknowledges the support of The Ove Arup Foundation and The Royal Academy of Engineering. The Scottish Funding Council is acknowledged for its support of the Joint Research Institute in Civil and Environmental Engineering, part of the Edinburgh Research Partnership in Engineering and Mathematics (ERPem). The support from UK India Education and Research Initiative project IND/CONT/07-08/E/133 is also acknowledged.

REFERENCES

1. Bisby, L., Dent, A., Green, M., Comparison of confinement models for fiber-reinforced-polymer-wrapped concrete. *ACI Struct J*, **102**(1), 62-72 (2005).
2. DeLorenzis, L., Tepfers, R., Comparative Study of Models on Confinement of Concrete Cylinders with Fiber-Reinforced Polymer Composites. *ASCE J of Comps for Constr*, **7**(3), 219-237 (2003).

3. Bisby, L., Green, M., Kodur, V., Fire endurance of fiber-reinforced polymer-confined concrete columns. *ACI Struct J*, **102(6)**, 883-891 (2005).
4. Chowdhury, E., Bisby, L., Green, M., Kodur, V., Investigation of insulated FRP-wrapped reinforced concrete columns in fire. *Fire Safety J*, **42(6)**, 452-460 (2007).
5. Yaqub, M., Bailey, C., Repair of fire damaged circular reinforced concrete columns with FRP composites. *Construction & Building Mat*, **25**, 359-370 (2011).
6. Fletcher, I., Carvel, R., Welch, S., Torero, J., The behaviour of concrete structures in fire. *Thermal Sci*, **11(2)**, 33-57 (2007).
7. Concrete Society, *Assessment, Design and Repair of Fire-Damaged Concrete Structures, TR 68*, The Concrete Society, UK (2008).
8. Buchanan, A., *Structural design for fire safety*, John Wiley & Sons, UK (2001).
9. Naus, D., *The Effect of Elevated Temperature on Concrete Materials and Structures – A Literature Review*, Oak Ridge National Laboratory, USA (2001).
10. CEN. *Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural fire design*, European Committee for Standardization, Belgium (2004).
11. Freskakis, G., Burrow, R., Debbas, E., Strength Properties of Concrete at Elevated Temperature. Presented at *Civil Engineering Nuclear Power, ASCE National Convention*, Boston, USA, 1979.
12. ACI. *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*, American Concrete Institute, USA (2008).
13. www1.gilar.co.il/PDF/English/Wrap_Hex_230C_e.pdf (accessed Dec 1, 2010).
14. CLG. *Approved Document B – Volume 2 – Buildings other than dwelling houses*, Department for Communities and Local Government, UK (2006).
15. ISO. *Fire-resistance tests – Elements of building construction – Part 1: General requirements*, International Organization for Standardization, Switzerland (1999).
16. Bisby, L., Take, W. Strain Localizations in FRP Confined Concrete: New Insights. *Structures & Buildings*, **162**, 301-309 (2009).
17. White, D., Take, W., Bolton, M. Soil deformation measurement using Particle Image Velocimetry & photogrammetry. *Geotechnique*, **53(7)**, 619-632 (2003).
18. Take, W., Kemp J., Application of digital image-based deformation measurements to geotechnical testing. *Proc 59th Canadian Geotechnical Conference*, Vancouver, Canada, 2006.
19. Bisby, L., Stratford, T., The Ultimate Strain of FRP Confined Concrete Columns: New Experimental Observations and Insights. *5th Int Conf on FRP Composites in Civil Engineering*, Beijing, China, 2010.
20. Mandal, S., Hoskin, A., Fam, A., Influence of Concrete Strength on Confinement Effectiveness of Fiber-Reinforced Polymer Circular Jackets. *ACI Structural J*, **102(3)**, 383-392 (2005).
21. Mohamed Ali, M., Oehlers, D., Griffith, M., The Residual Strength of Confined Concrete. *Advances in Struct Engrg*, **13(4)**, 603-618 (2010).
22. Lam, L., Teng, J.G., Ultimate condition of fiber reinforced polymer-confined concrete. *J Composites for Constr*, **8(6)**, 539-548 (2004).
23. Chen, J.F., Ai, J., Stratford, T., Effect of geometric discontinuities on strains in FRP wrapped columns, *J Composites for Constr*, **14(2)**, 136-145 (2010).